Title: The spins of binary black holes following LIGO and Virgoâ€™s third observing run

Speakers: Andrea Biscoveanu

Series: Strong Gravity

Date: November 11, 2021 - 1:00 PM

URL: https://pirsa.org/21110010

Abstract: The growing catalog of gravitational wave signals from binary black hole mergers has allowed us to probe the properties of these compact objects more precisely than ever before. In particular, binary black hole spin measurements have the potential to reveal the formation channels of these systems. An accurate and precise measurement of the spins of individual merging black holes is required to model their population-level distributions. In this talk, I will discuss recent work on the measurability of individual black hole spins focusing on those in heavy binaries. I will also present novel spin parameterizations that facilitate the study of specific features of binary black hole evolutionary histories. I will contextualize these individual spin measurements within the observed population of binary black holes and conclude by presenting the latest LIGO-Virgo results for the black hole spin distribution.

The spins of binary black holes following LIGO and Virgo's third observing run

Sylvia Biscoveanu

11/11/2021

Perimeter Institute Strong Gravity Seminar Series

Collaborators: Max Isi, Vijay Varma, Salvatore Vitale, Will Farr

@sylvia_bisco

sbisco@mit.edu

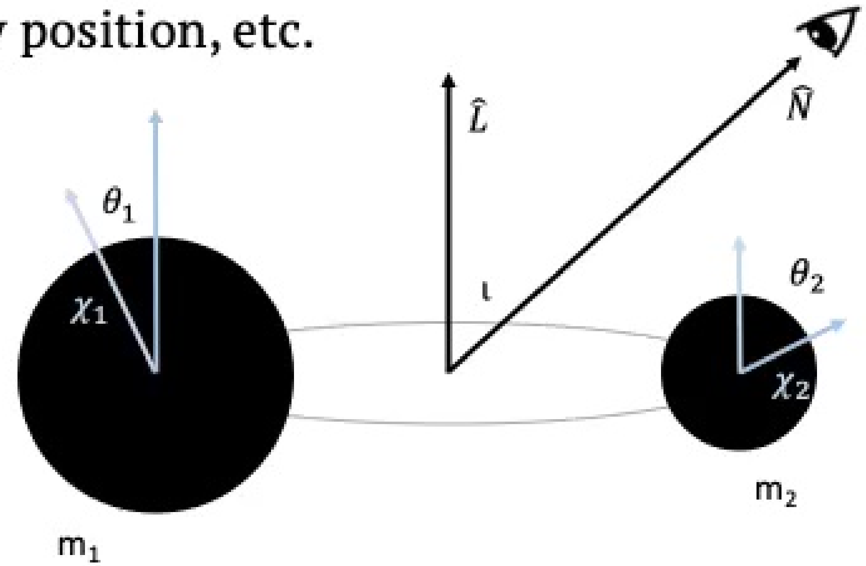
MIT Kavli Institute
for Astrophysics
and Space Research

LIGO

Binary Black Holes

- Quasicircular binary black hole systems detected by LIGO in gravitational-waves are characterized by 15 parameters
  - Intrinsic – masses and spins
  - Extrinsic – distance, inclination, sky position, etc.

- Precession occurs when individual spins are misaligned to the orbital angular momentum

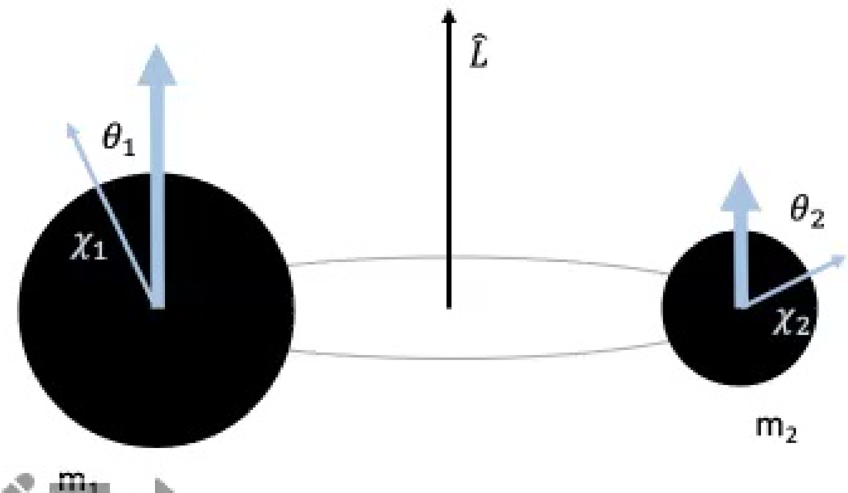


2

Spin Parameters

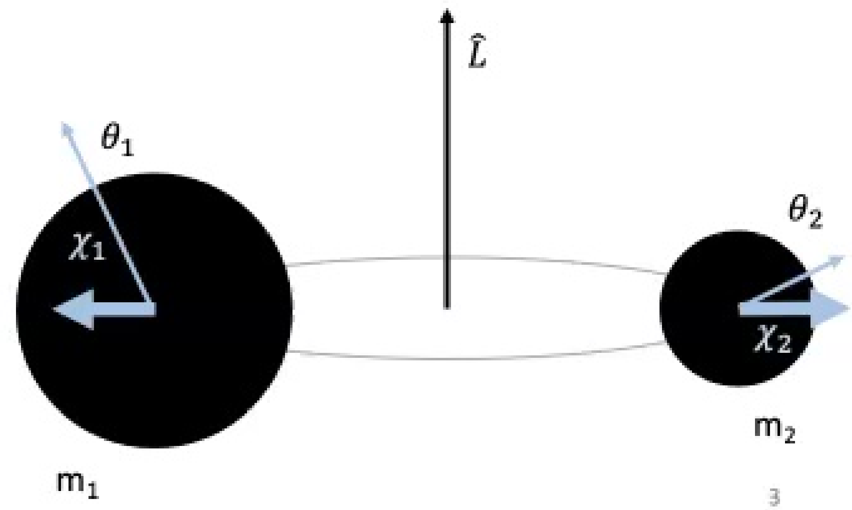
- χ_{eff} - best measured spin parameter with gravitational waves, mass-weighted spin aligned with the orbital angular momentum

$$\chi_{\text{eff}} = \frac{\chi_1 \cos\theta_1 + q\chi_2 \cos\theta_2}{1+q}$$



- χ_p - effective precessing spin, mass-weighted spin projection onto the orbital plane

$$\chi_p = \max\left(\chi_1 \sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q\chi_2 \sin\theta_2\right)$$

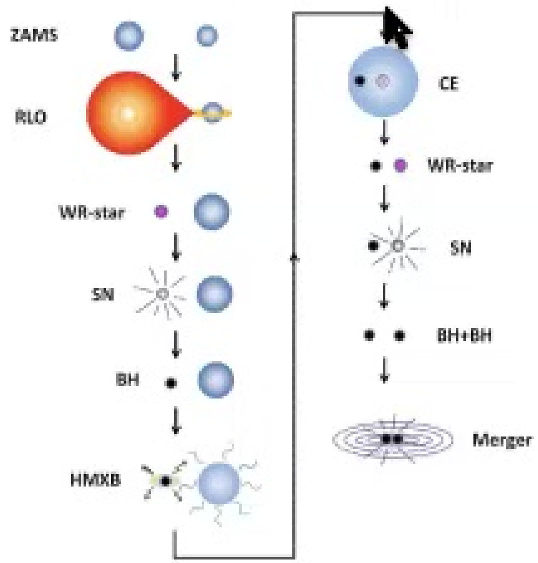


3

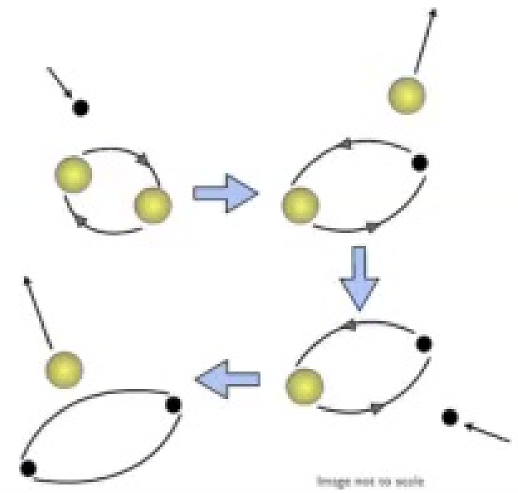
Astrophysical Implications

- Spins carry important signatures of compact binary formation channel

Field formation:
Preferentially aligned spins



Dynamical formation:
Isotropically distributed spins



- Using χ_{eff} and χ_p for population studies results in loss of information

Images: http://www-astro.physics.ox.ac.uk/~podsi/grav_waves.pdf

4

Overview

- Measuring the spin parameters of individual heavy binary black hole systems
- Alternative parameterizations for improving measurements of
  - The azimuthal spin angles projected onto the orbital plane
  - The component spins for near equal-mass systems
- Latest constraints on the population-level distributions of binary black hole spins

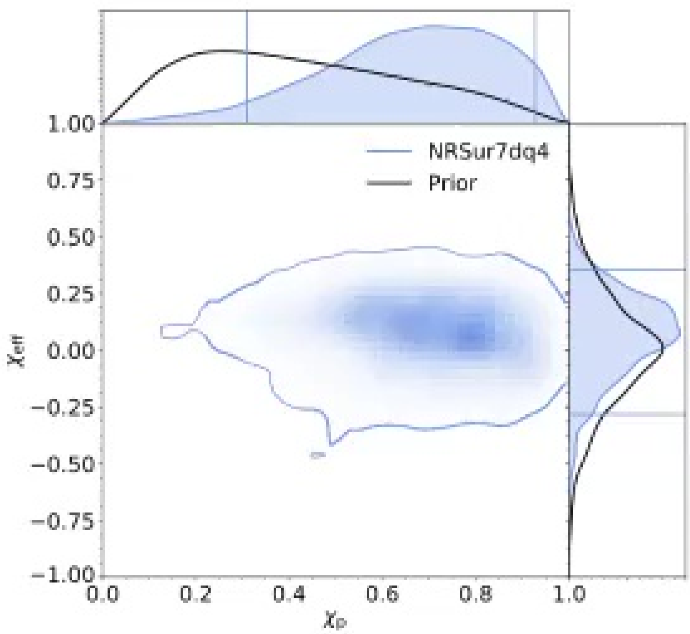
Heavy BBH Spin Measurements

- Spin measurements so far have been largely uninformative both for component spin parameters and for χ_p
- Developments in waveform modeling have led to new approximants that include the effects of both higher order modes and precession, including the full six-dimensional spin parameters
- GW190521 poses an interesting question of how χ_p can be measured so well for a system that is so heavy and not particularly loud
- Our goal: conduct a systematic parameter estimation study of the measurability of spin for heavy BBH systems using the NRSur7dq4 waveform model

S.B, Isi, Varma, Vitale, arxiv:2106.06492 6

Measuring χ_p in highly precessing systems

- Why is the χ_p posterior so well-constrained for GW190521 when it's so massive and relatively weak (SNR~15)?

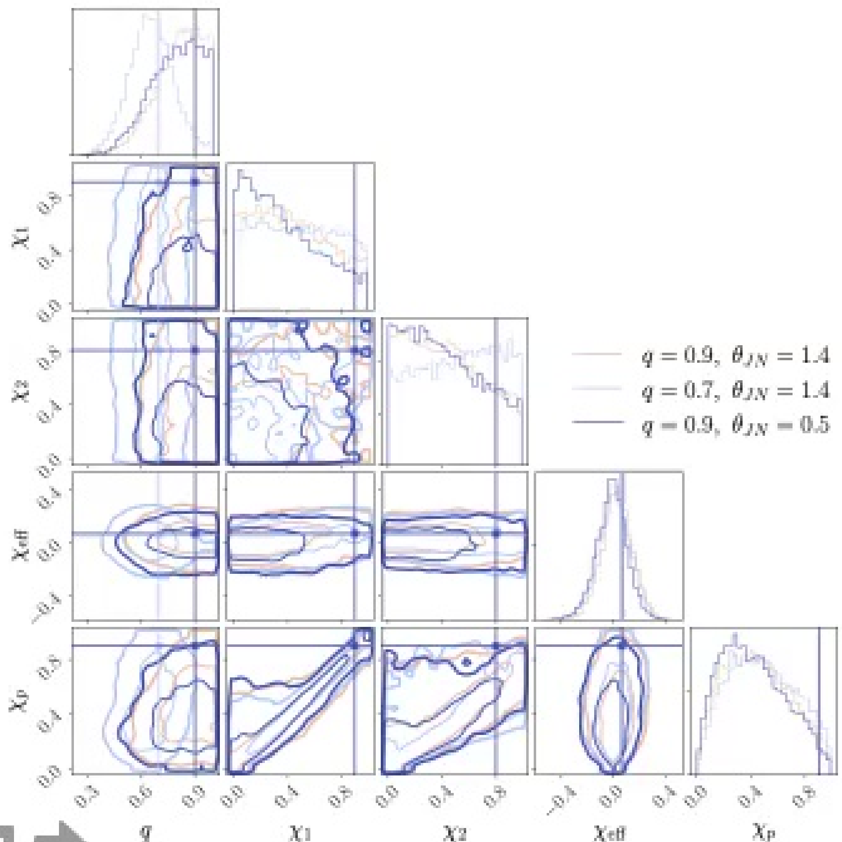


Abbott et al. 2020 arxiv:2009.01075

- Simulate similar systems in a HLV detector network at design sensitivity, keeping network SNR=15
  - Nearly edge-on, nearly equal mass
    - $\theta_{JN} = 1.4, q = 0.9$
  - Nearly face-on, nearly equal mass
    - $\theta_{JN} = 0.5, q = 0.9$
  - Nearly edge-on, more unequal masses
    - $\theta_{JN} = 1.4, q = 0.7$
  - $\chi_p = 0.9$ for all simulations

7

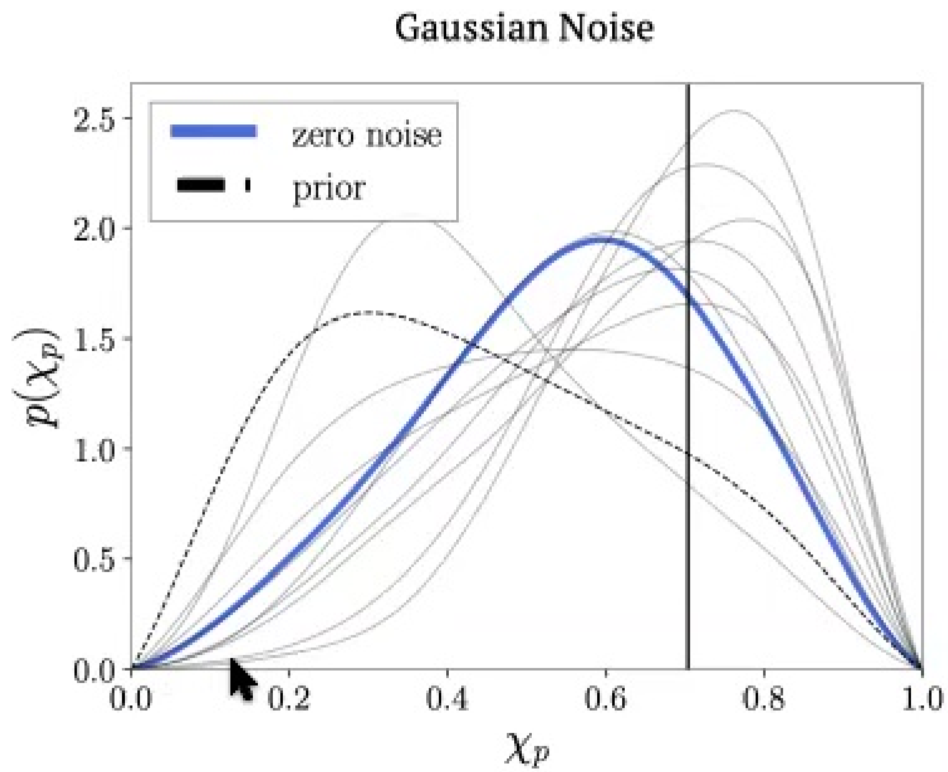
Measuring χ_p in highly precessing systems



- Spin magnitude posteriors prefer low values for both components (less so for unequal-mass case)
- χ_p shows basically no deviation from the prior
- Maybe informative GW190521 measurement is driven by noise at time of event?

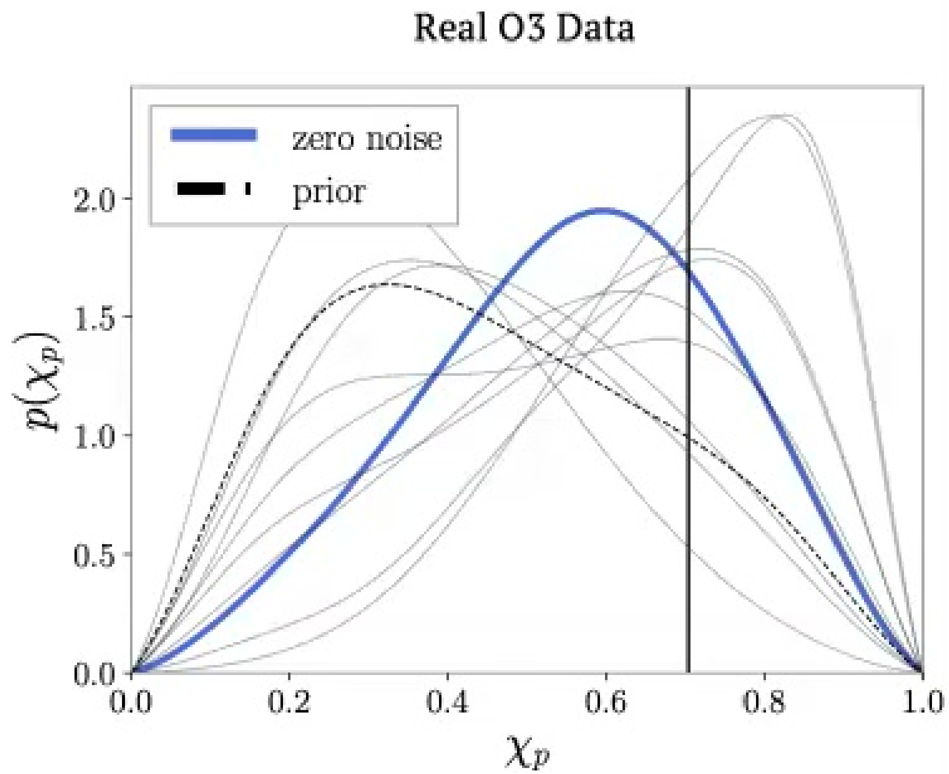
Effect of Noise on Measurability of Precession

- Inject maximum-likelihood posterior sample from GW190521 into 10 different realizations of Gaussian noise and 10 different times during O3a
  - Gaussian noise colored by PSD from GW190521, HLV network
  - Real noise using only HL (V not always available), choose distance keeping network SNR ~ 15
  - $\chi_p = 0.7$, $\chi_1 = 0.09$, $\chi_2 = 0.90$
  - The exact spin configuration can have a significant effect on the measurability



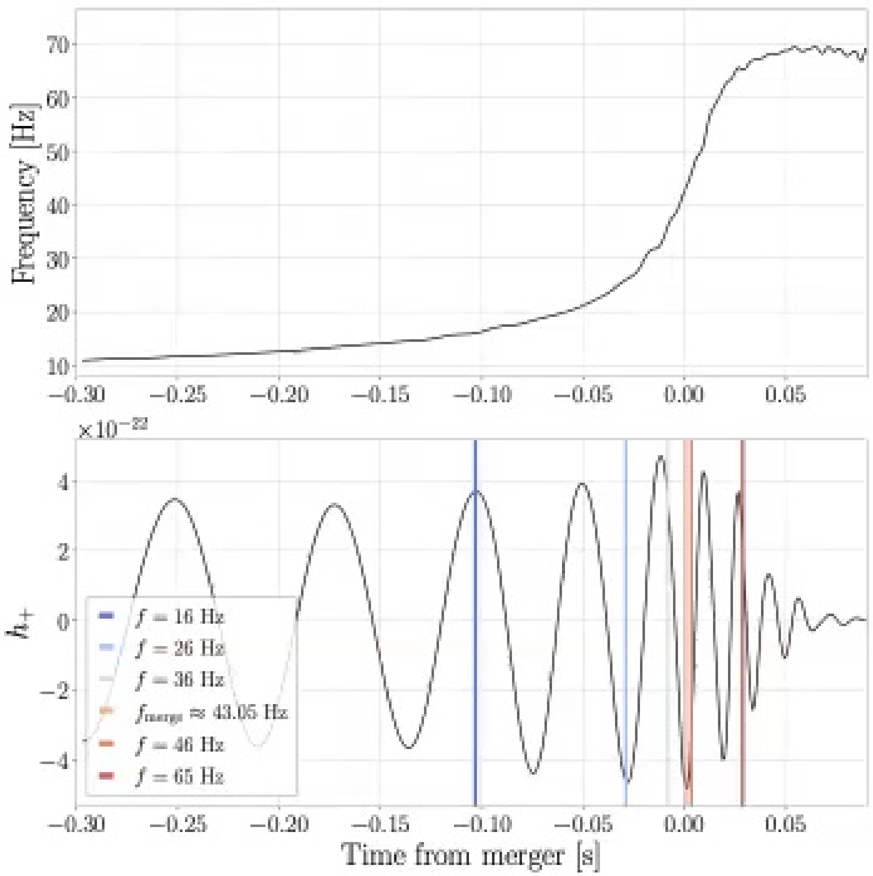
Effect of Noise on Measurability of Precession

- Inject maximum-likelihood posterior sample from GW190521 into 10 different realizations of Gaussian noise and 10 different times during O3a
  - Gaussian noise colored by PSD from GW190521, HLV network
  - Real noise using only HL (V not always available), choose distance keeping network SNR ~ 15
  - $\chi_p = 0.7$, $a_1 = 0.09$, $a_2 = 0.90$
  - The exact spin configuration can have a significant effect on the measurability



10

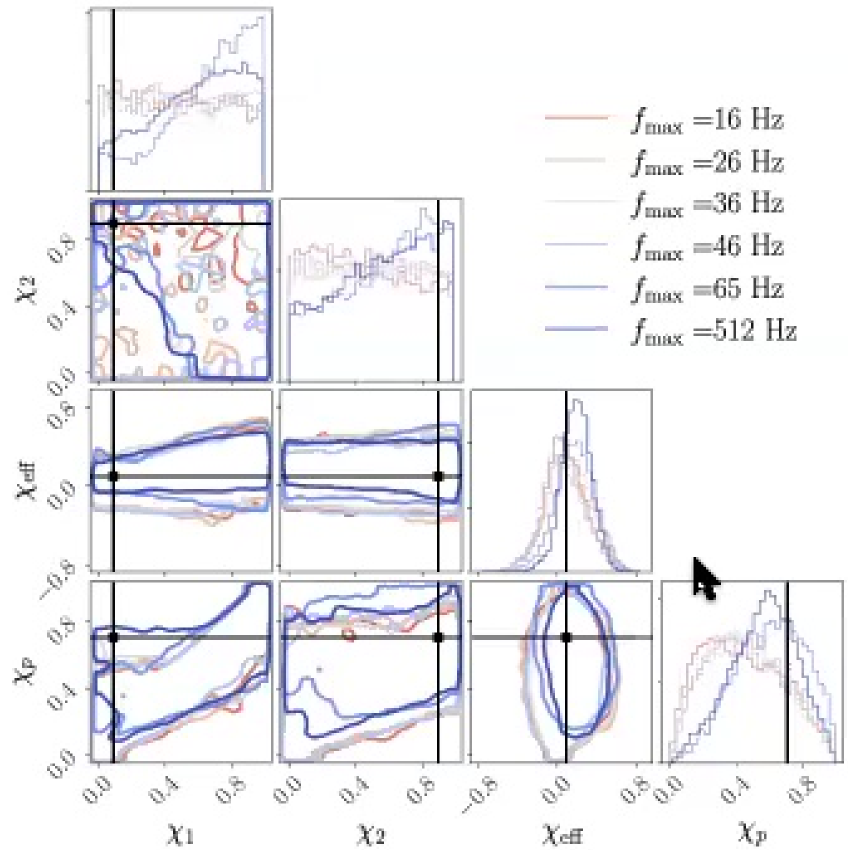
Effect of cutoff frequency



- Which part of the frequency band drives the measurement of the spin parameters for high-mass systems?
- Repeat the GW190521 maximum-likelihood simulation using different maximum frequencies keeping SNR constant and $f_{\text{min}} = 11$ Hz
- System merges at ~43 Hz

Effect of cutoff frequency

- Posteriors for all parameters remain largely unchanged until $f_{\max}$ = 65 Hz is reached
- Even for maximum frequencies of 46 and 50 Hz, which are above the merger frequency
- Ringdown part of signal where time-frequency evolution changes contributes most to the spin measurement for this system



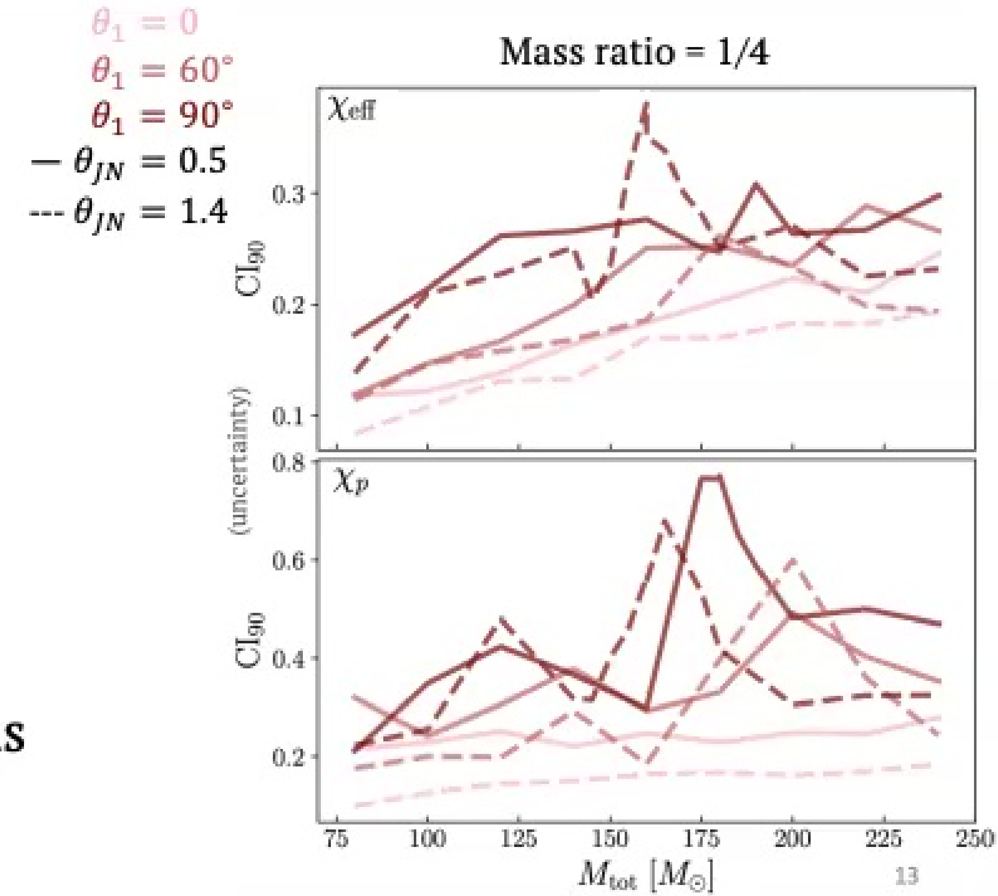
12

Dependence on mass

- Simulate systems with…
  - $\chi_1 = 0.8, \ \chi_2 = 0$
  - $f_{\text{ref}} = 25$ Hz
  - Network SNR=30

… across a range of tilt angles, inclinations, and masses

- Spins better constrained for systems with
  - Aligned spins
  - Edge-on inclinations
  - Unequal masses
- Constraint generally degrades as total mass increases

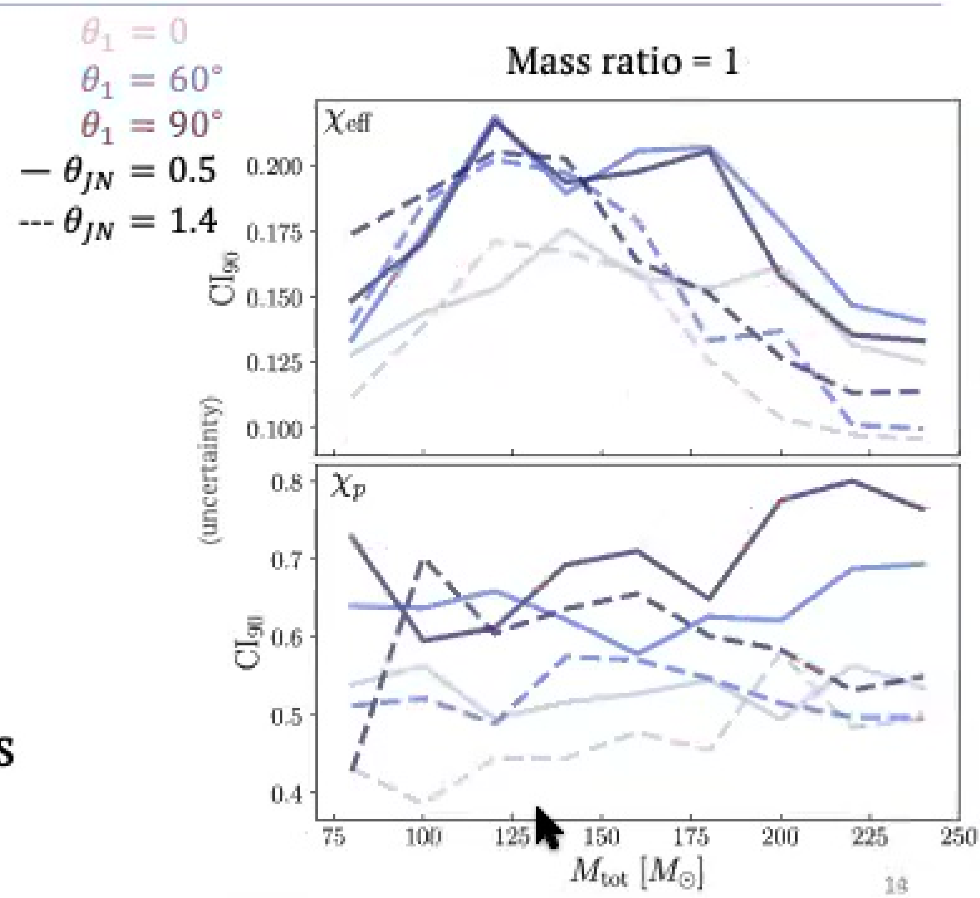


Dependence on mass

- Simulate systems with…
  - $\chi_1 = 0.8,\ \chi_2 = 0$
  - $f_{ref} = 25$ Hz
  - Network SNR=30

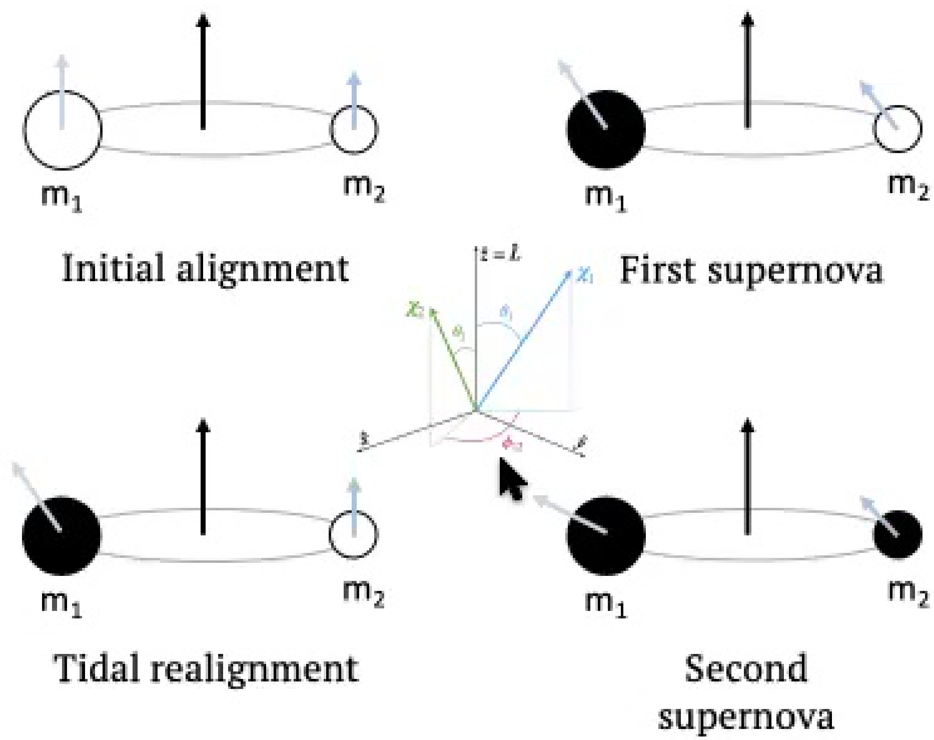
… across a range of tilt angles, inclinations, and masses

- Spins better constrained for systems with
  - Aligned spins
  - Edge-on inclinations
  - Unequal masses
- Constraint generally degrades as total mass increases

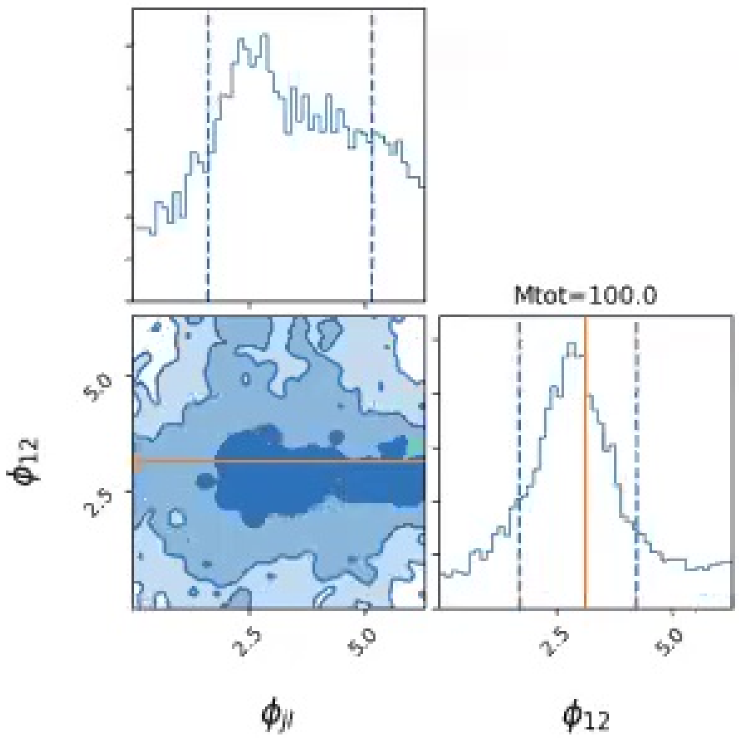


Measurement of ϕ_{12}

- Measuring ϕ_{12} has implications for binary formation channels, since binaries locked in spin-orbit resonances due to efficient tides tend to have $\phi_{12} = 0, \pm\pi$
- If more massive star is now the more massive black hole, BBH population drawn to $\phi_{12} = \pm\pi$
- If more massive star is now the less massive black hole due to mass transfer, BBH population drawn to $\phi_{12} = 0$

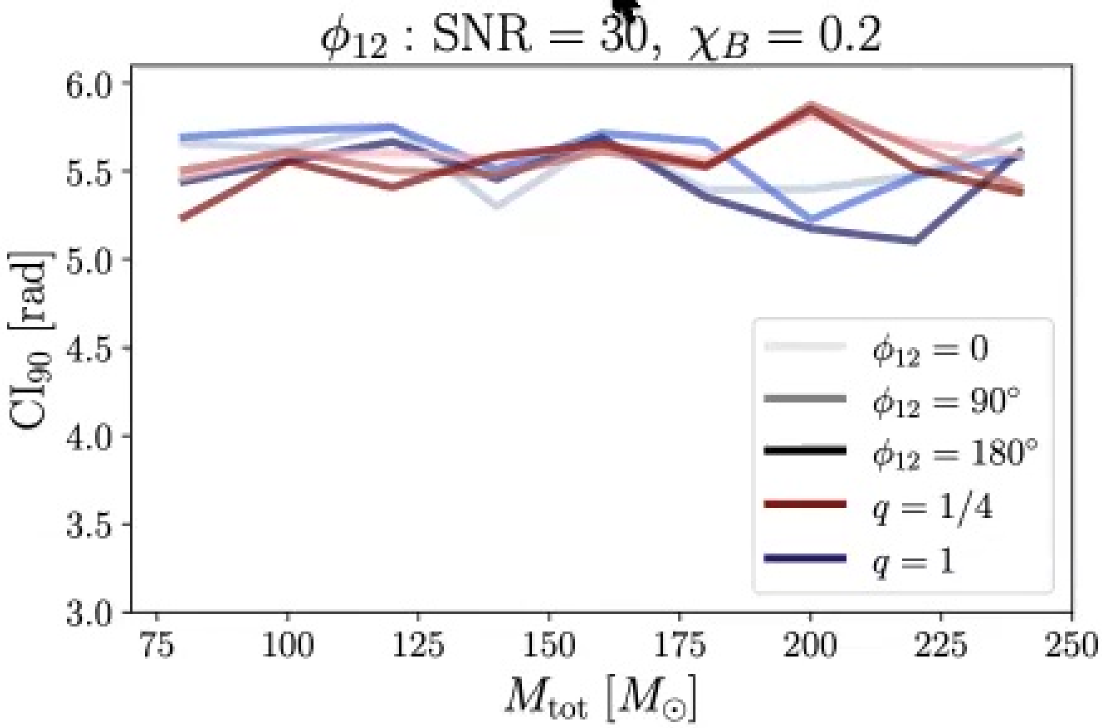


Measurement of ϕ_{12}



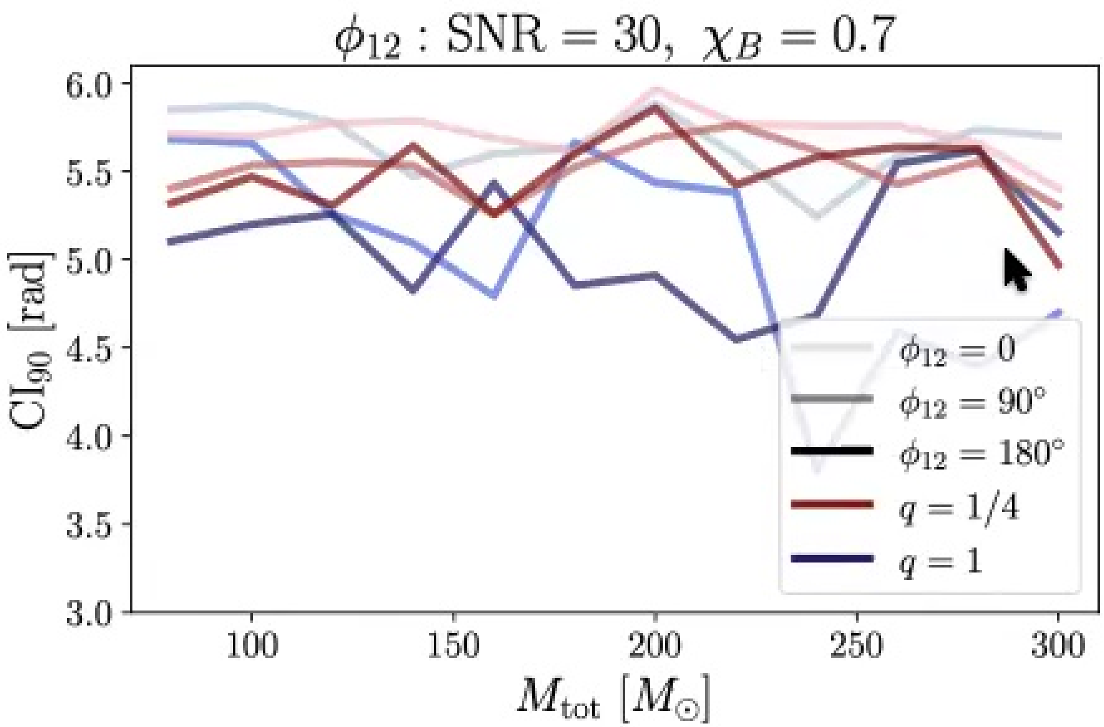
- We don't necessarily simulate resonant configurations, but we can determine how well ϕ_{12} can be measured with NRSur7dq4
- ϕ_{12} has no physical meaning in simulations with a nonspinning secondary, but it seems to be well-constrained for systems with $\theta_1 = 0, \theta_{JN} = 1.4, q = 1$
- Lack of precession is informative → potential preference for $\phi_{12} = \pi$ among aligned-spin systems

Measurement of ϕ_{12}



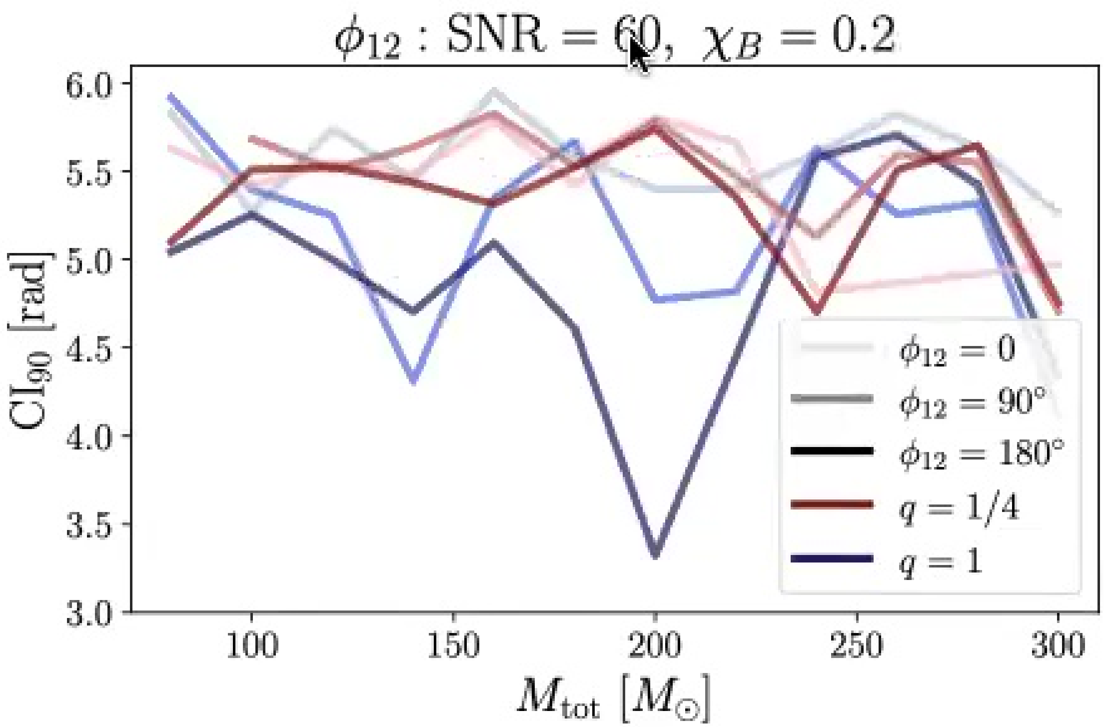
- Change simulation parameters to add secondary spin with three different values of $\phi_{12} = 0, \frac{\pi}{2}, \pi$
- ϕ_{12} is in general difficult to measure at a fixed reference frequency of 25 Hz even for systems with high secondary spin and high SNR

Measurement of ϕ_{12}



- Change simulation parameters to add secondary spin with three different values of $\phi_{12} = 0, \frac{\pi}{2}, \pi$
- ϕ_{12} is in general difficult to measure at a fixed reference frequency of 25 Hz even for systems with high secondary spin and high SNR

Measurement of ϕ_{12}



- Change simulation parameters to add secondary spin with three different values of $\phi_{12} = 0, \frac{\pi}{2}, \pi$
- ϕ_{12} is in general difficult to measure at a fixed reference frequency of 25 Hz even for systems with high secondary spin and high SNR

Conclusions – Heavy BBH Spins

- The measurability of $\chi_{\rm p}$ depends on the exact six-dimensional spin configuration
  - Which configurations lead to the most informative spin measurements?
- The spin information for GW190521-like systems depends strongly on the merger-ringdown parts of the signal
- Spin constraints improve for systems with aligned spins, edge-on inclinations, and unequal masses, but get worse with increasing mass in the range $M_{\rm tot} = 80 - 240\ M_{\odot}$
- ϕ_{12} is in general difficult to measure at a fixed reference frequency

S.B, Isi, Varma, Vitale, arxiv:2106.06492 20

Overview

- Measuring the spin parameters for individual heavy binary black hole systems
- Alternative parameterizations for improving measurements of
  - The azimuthal spin angles projected onto the orbital plane
  - The component spins for near equal-mass systems
- Latest constraints on the population-level distributions of binary black hole spins

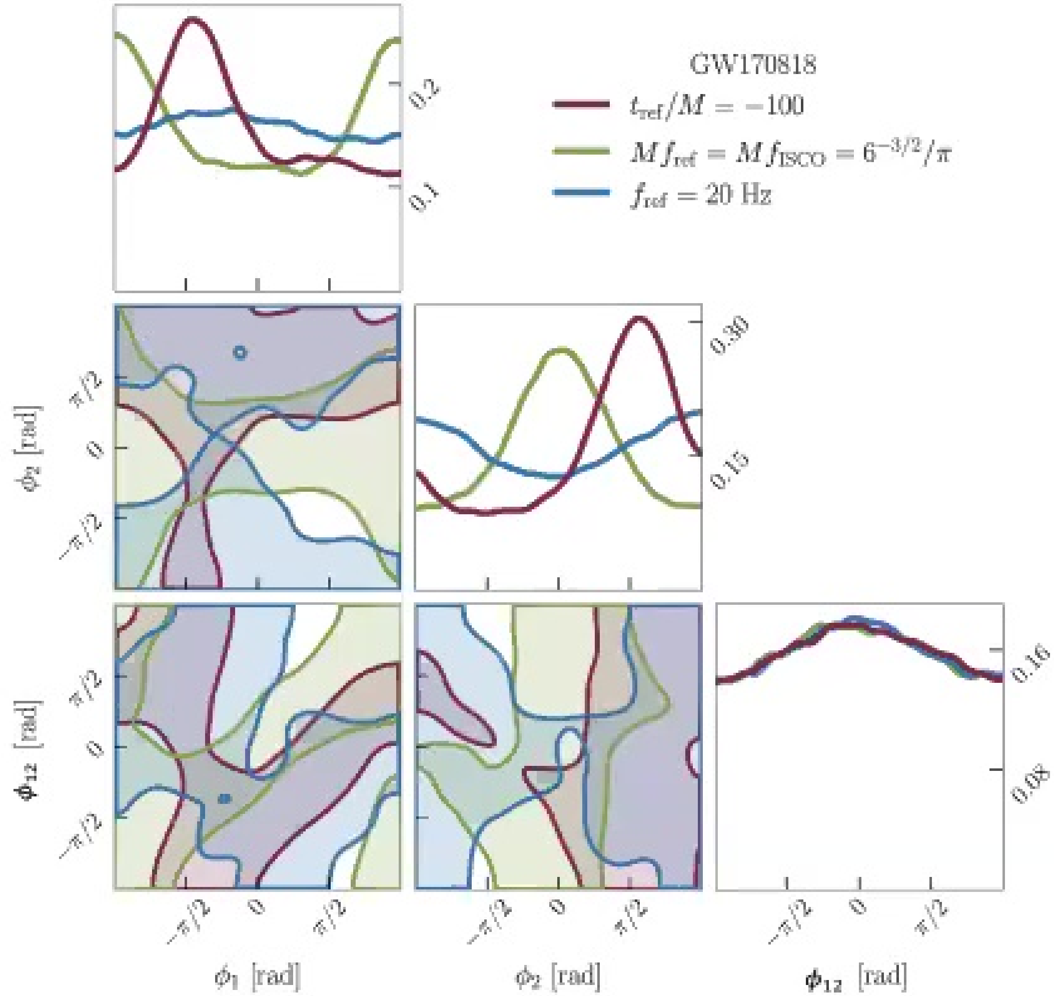
Measurement of azimuthal spins

- Previous results indicate that ϕ_{12} is difficult to measure at a reference frequency of 25 Hz
- Instead, choose a reference point where the waveform is more sensitive to variations in the spin parameters, closer to merger
  - Dimensionless frequency, $Mf_{\mathrm{ref}} = Mf_{\mathrm{ISCO}} = 6^{-3/2}/\pi$
  - Dimensionless time, $t_{\mathrm{ref}}/M = -100$ (~few cycles before merger)
- NRSur7dq4 waveform model is the optimal choice for measuring the in-plane spin angles because it is tuned to precessing numerical relativity simulations

Varma, Isi, **S.B**, Farr, Vitale, arxiv:2107.09692

GW170818

- Data is individually informative about either ϕ_1 or ϕ_2 but not necessarily both at the same time
- Significant correlations between the three parameters but 2D credible regions are smaller closer to merger

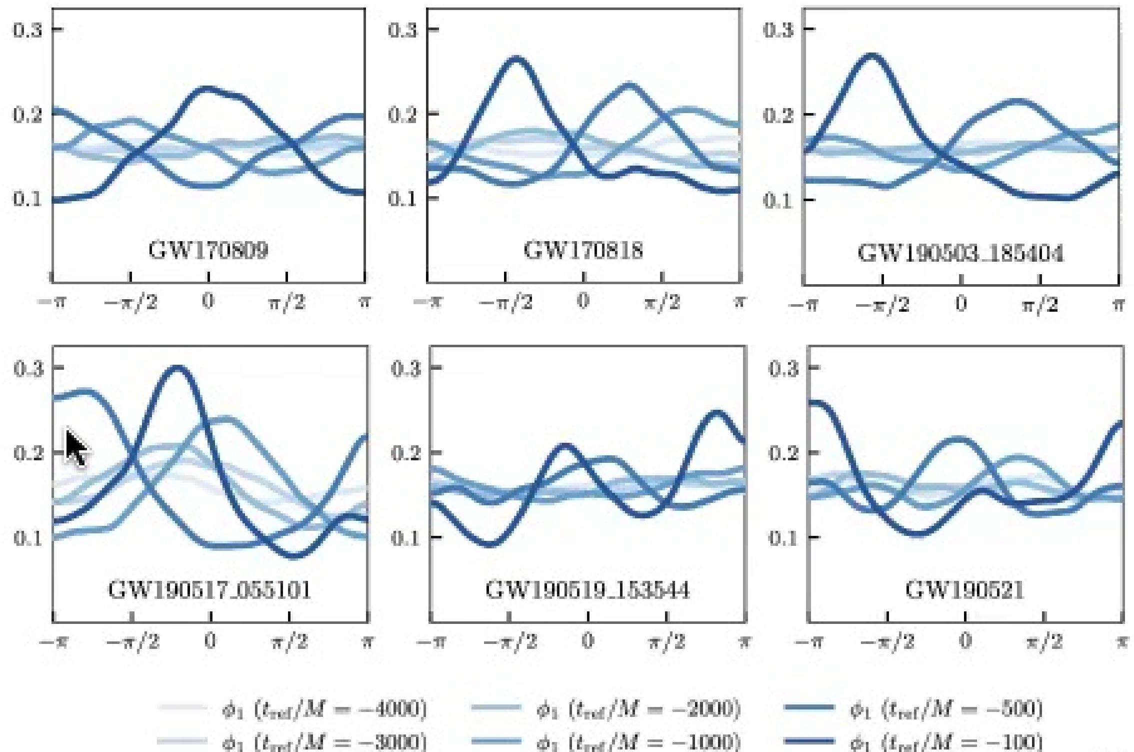


23

Finding the optimal reference point

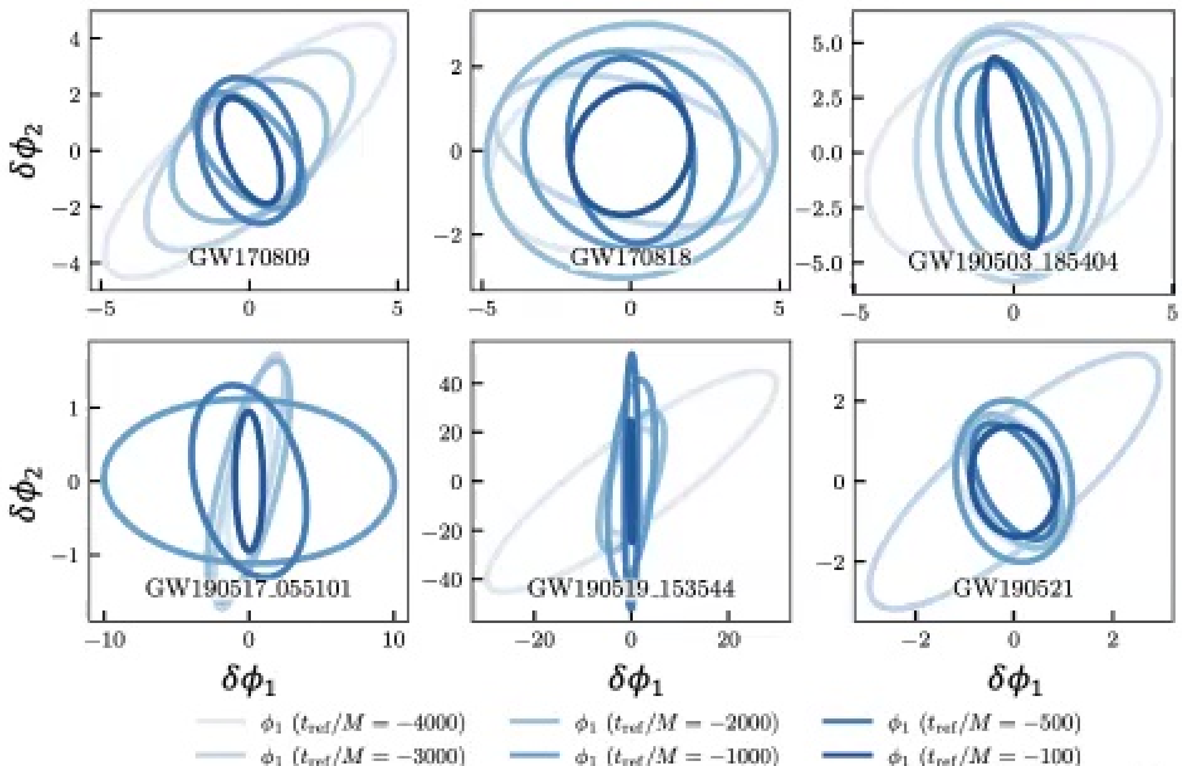
- Posterior on ϕ_1 narrows as the reference point approaches

  $t_{\mathrm{ref}}/M = -100$
- Orbital and precession timescales decrease nearer to merger, so waveform is more sensitive to changes in ϕ_1



Finding the optimal reference point

- Theoretical estimate of the statistical uncertainty in ϕ_1 and ϕ_2 using maximum-likelihood waveform for each event
- Uncertainty shrinks as reference point approaches merger



25

Conclusions – Azimuthal angles

- The azimuthal projections of the component spins onto the orbital plane are better measured at a reference point near the merger
- The waveform is more sensitive to variations in these angles nearer to merger since the orbital and precession timescales are smaller
- Not generating new information, merely asking a question that is easier to answer at current detector sensitivities

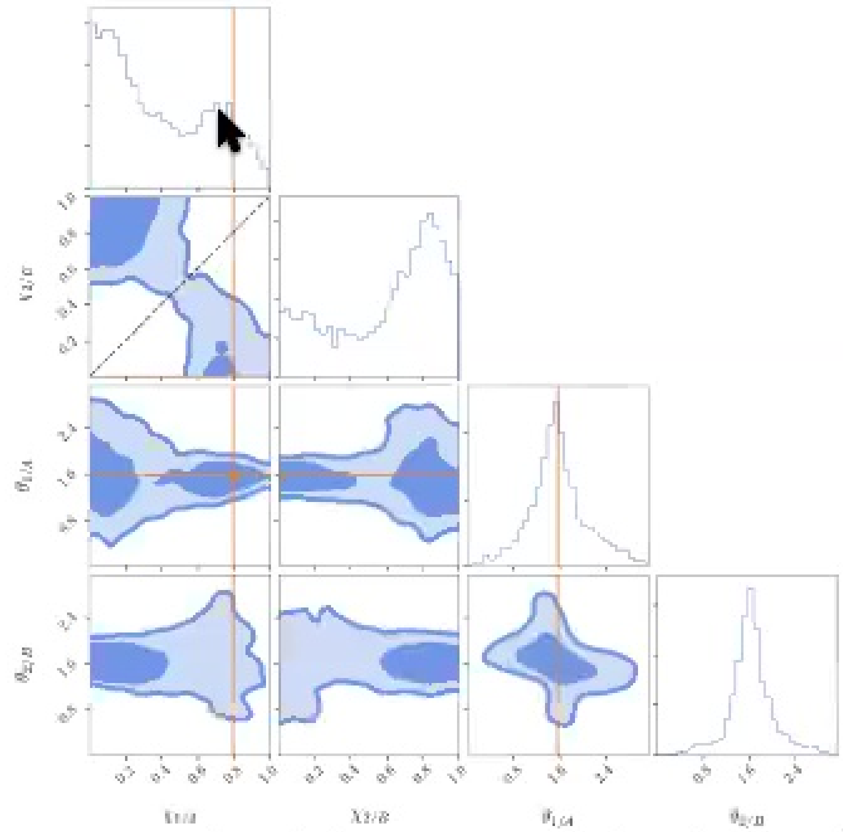
Varma, Isi, **S.B**, Farr, Vitale, arxiv:2107.09692

Overview

- Measuring the spin parameters for individual heavy binary black hole systems
- Alternative parameterizations for improving measurements of
  - The azimuthal spin angles projected onto the orbital plane
  - The component spins for near equal-mass systems
- Latest constraints on the population-level distributions of binary black hole spins

Spins of near-equal mass systems

- LVC analyses sort the components of a binary system into "primary" and "secondary" using their masses
- Priors enforce $m_1 > m_2$
- How do you distinguish the two objects when the system is consistent with equal mass?
- Simulated System:
  - $m_1 = m_2 = 40\ M_\odot$
  - $\chi_1 = 0.8, \chi_2 = 0, \theta_1 = 90°$, SNR=30

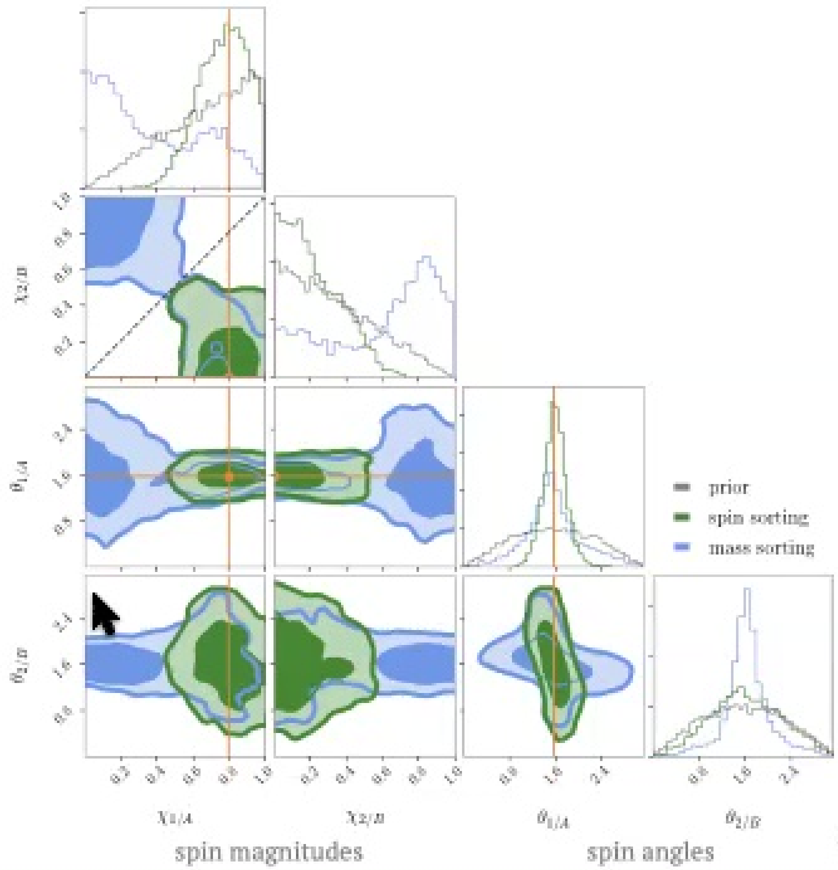


S.B, Isi, Varma, Vitale, arxiv:2007.09156

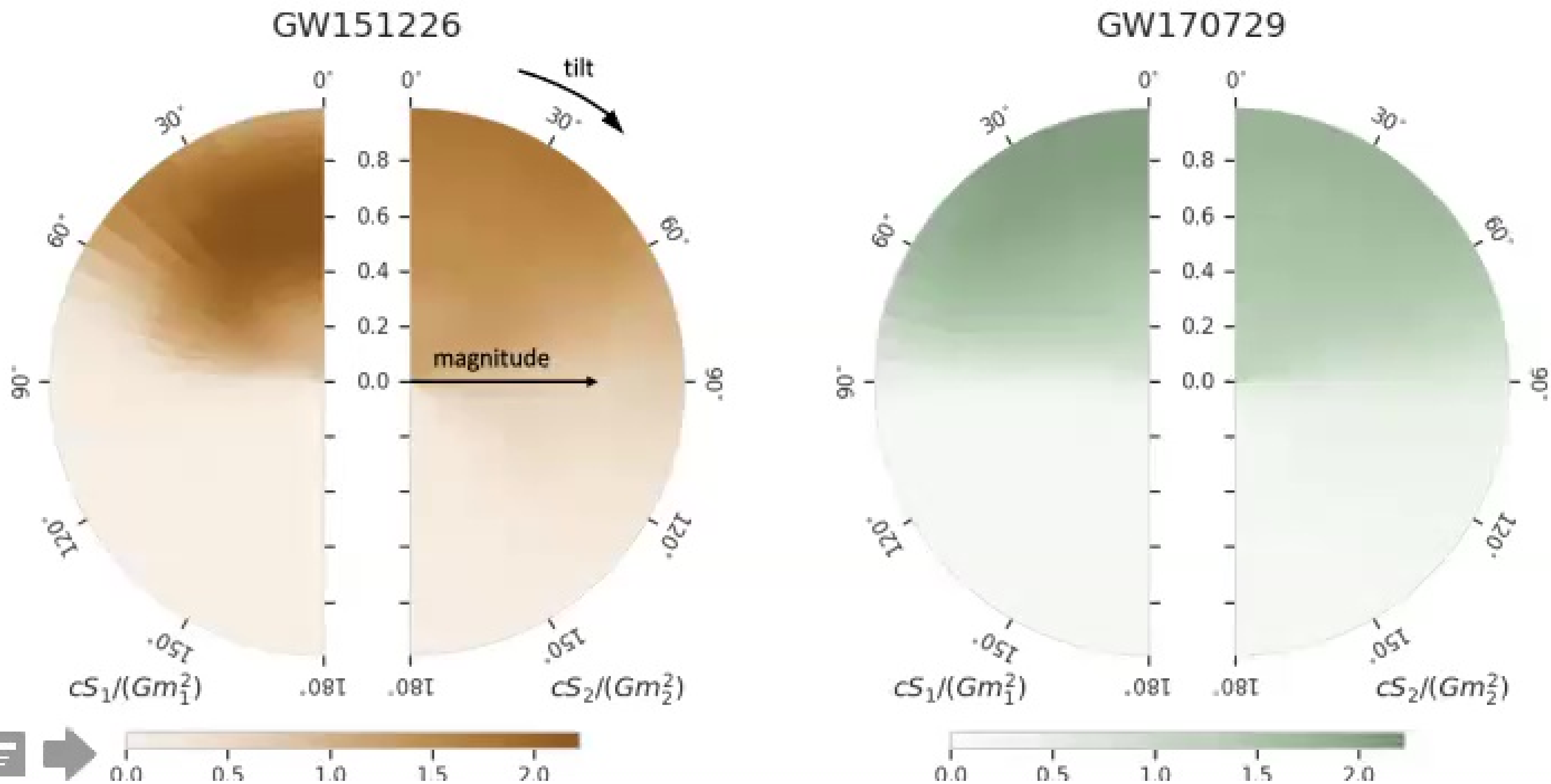
28

Spin sorting

- What if instead of sorting the objects by their mass, we sorted by spin?
- Now enforce $\chi_A > \chi_B$ and re-sort the samples for the other component properties as well
- Improvement in resolution of component spin quantities for generic systems with $q \sim 1$

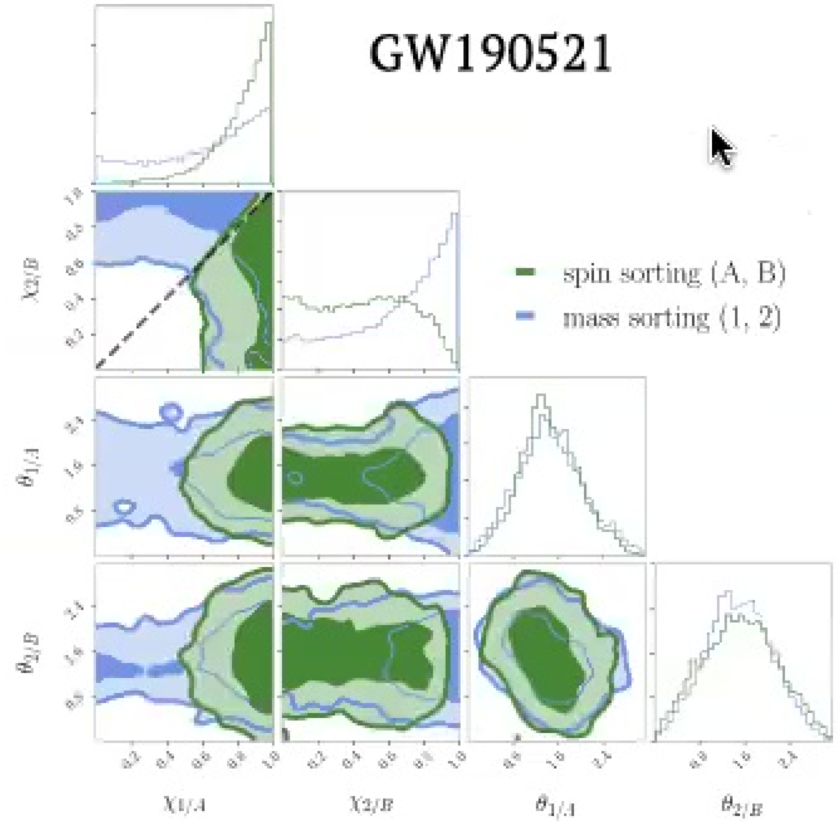


Individual detections – mass sorting



Application to current detections

- $\chi_A = 0$ ruled out at 90% credibility for events that already had support for nonzero spins
- Considerable support at Kerr limit for GW151226, GW170729, and GW190521
- Spin sorting isn't useful when looking at systems that have distinguishably unequal mass ratios



32

Conclusions and caveats – Spin sorting

- This is a very simple idea that doesn't add new information and can be done entirely in post-processing
- Changing the question from "What is the spin of the most massive black hole?" to "What is the spin of the most spinning black hole?" provides an improved spin constraint for near equal-mass systems
- Not just applying a new prior to existing parameters – defining a new set of parameters – hence no change in Bayesian evidence
- Does not change inferences about the effective aligned or precessing spins, χ_{eff} and χ_p

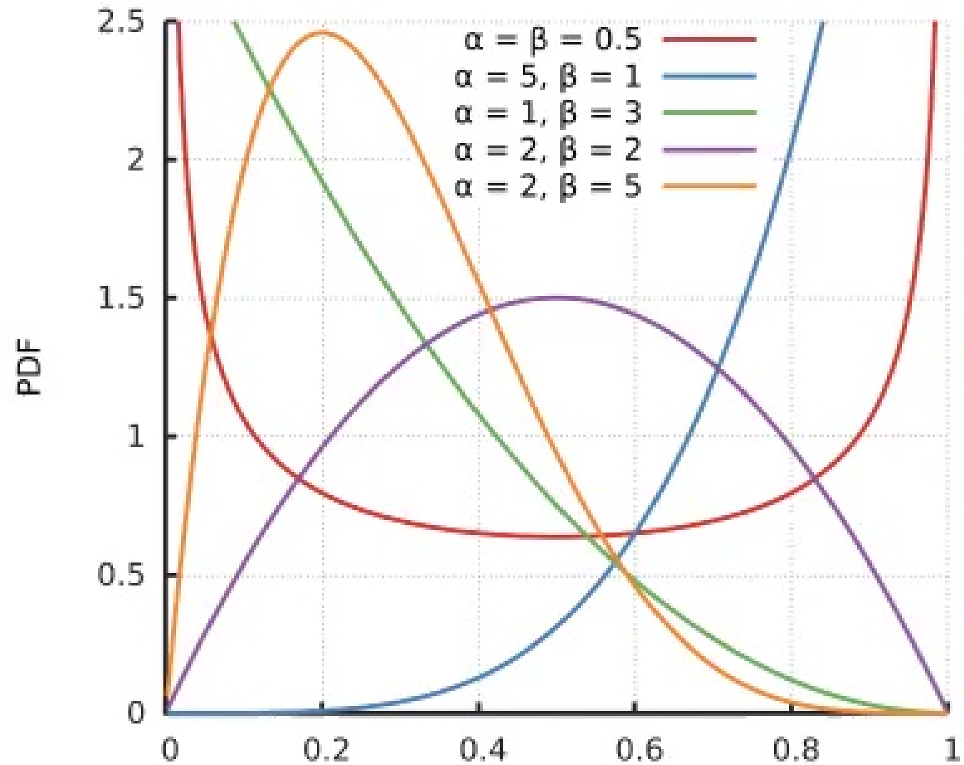
S.B, Isi, Varma, Vitale, arxiv:2007.09156 33

Population analysis

- Determine the distribution of spins across a population of detections instead of looking just at individual events
- Apply the new parameterizations for improved constraints on the distributions of the spin parameters
- BBHs detected during LIGO-Virgo's third observing run with false alarm rate < 1/yr:
  - GWTC-2 (up to first half of O3): 44 BBH
  - GWTC-3 (all O3): 69 BBH

Spin Magnitudes

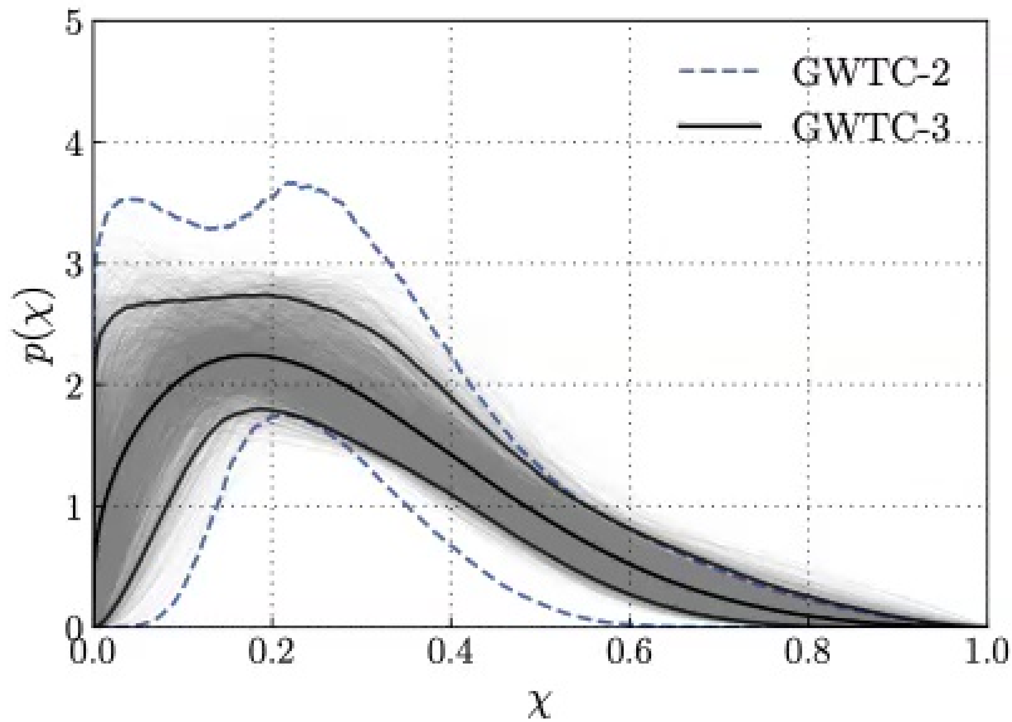
- Model the mass-sorted spin magnitudes as being drawn from the **same** Beta distribution (following Wysocki et al. arxiv:1805.06442)
- Infer the values of the hyper-parameters α and β using all the detections included in GWTC-3



36

Spin Magnitudes

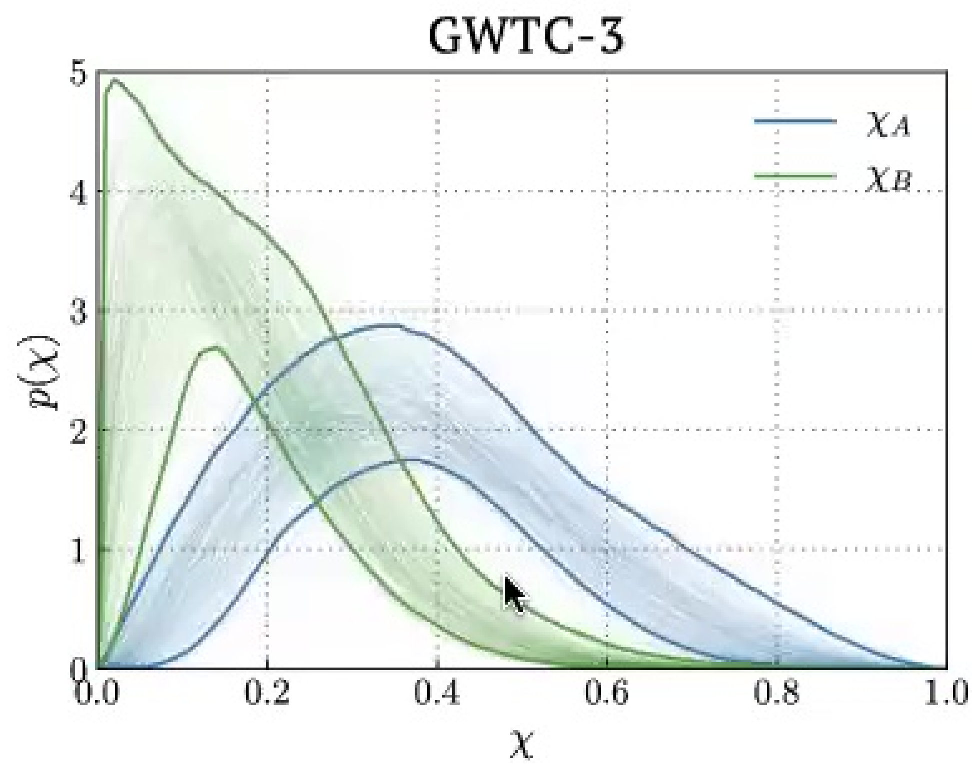
- Distribution of mass-sorted spins consistent with peaking at $\chi = 0$
- Infer the distributions of χ_A, χ_B assuming they're the maximum and minimum of 2 draws from the distribution of mass-sorted spins



LVK arxiv:2111.03634 37

Distributions of χ_A, χ_B

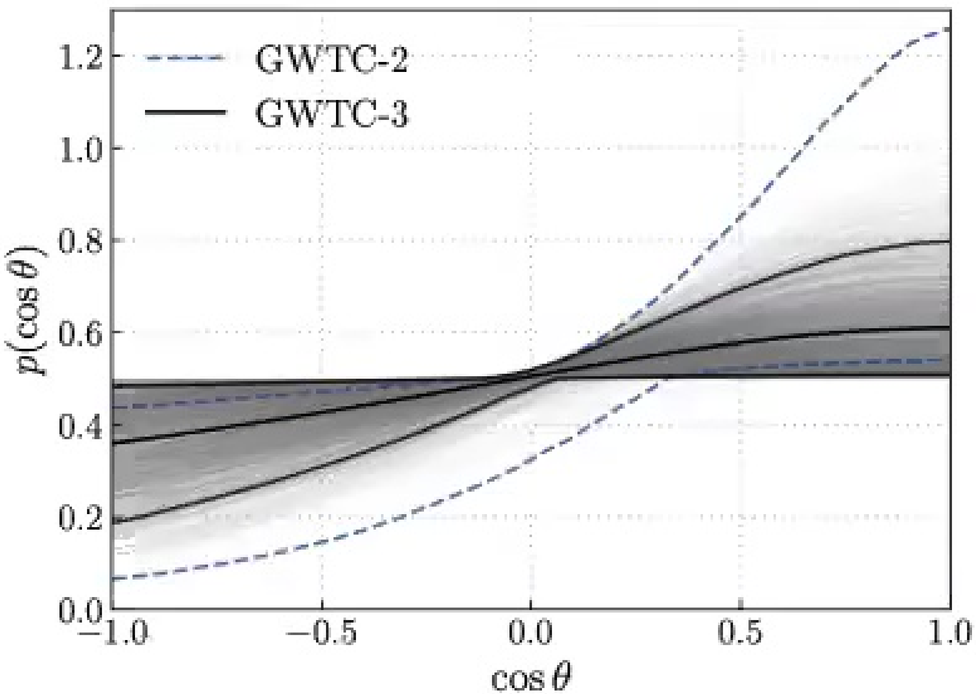
- $p(\chi_A)$ peaks away from $\chi = 0$, 99% of the highest-spinning black holes in LVC binaries have $\chi > 0.08$!
- $p(\chi_B)$ consistent with peaking at $\chi = 0$, 99% of probability below $\chi = 0.53$



LVK arxiv:2111.03634 38

Spin tilts

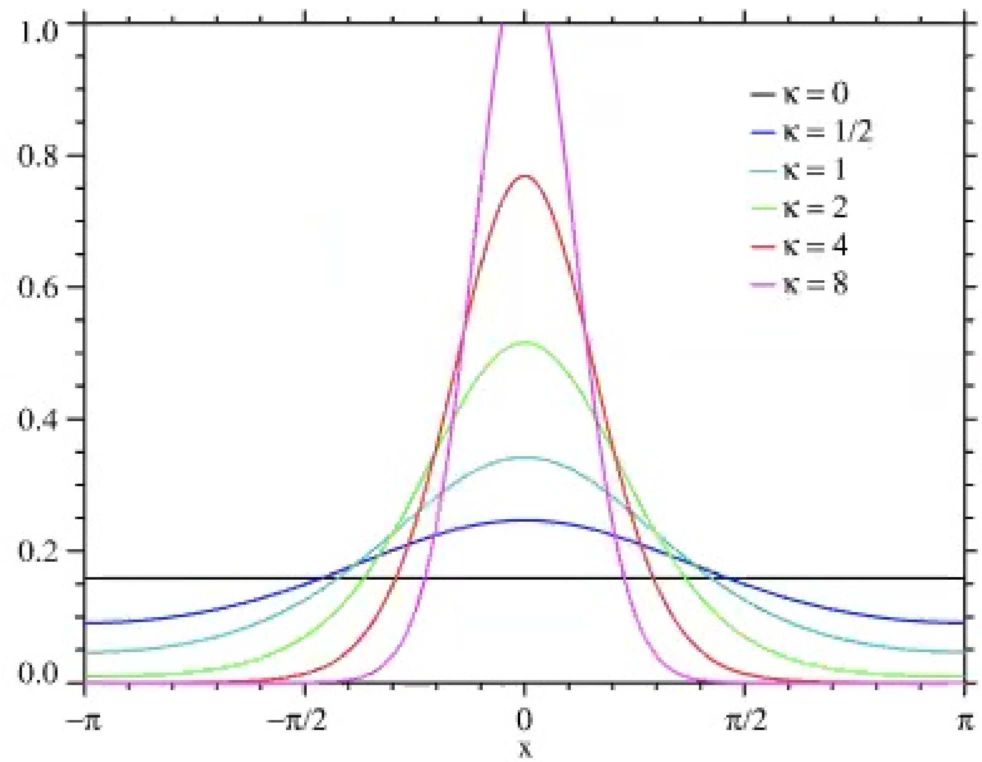
- Use a two-component model with preferentially aligned component and isotropic component (following Talbot et al. arxiv:1704.08370)
- GWTC-3 results favor a flatter distribution compared to GWTC-2, evidence for anti-aligned (negative) spins in the population



LVK arxiv:2111.03634 39

Azimuthal spin angles

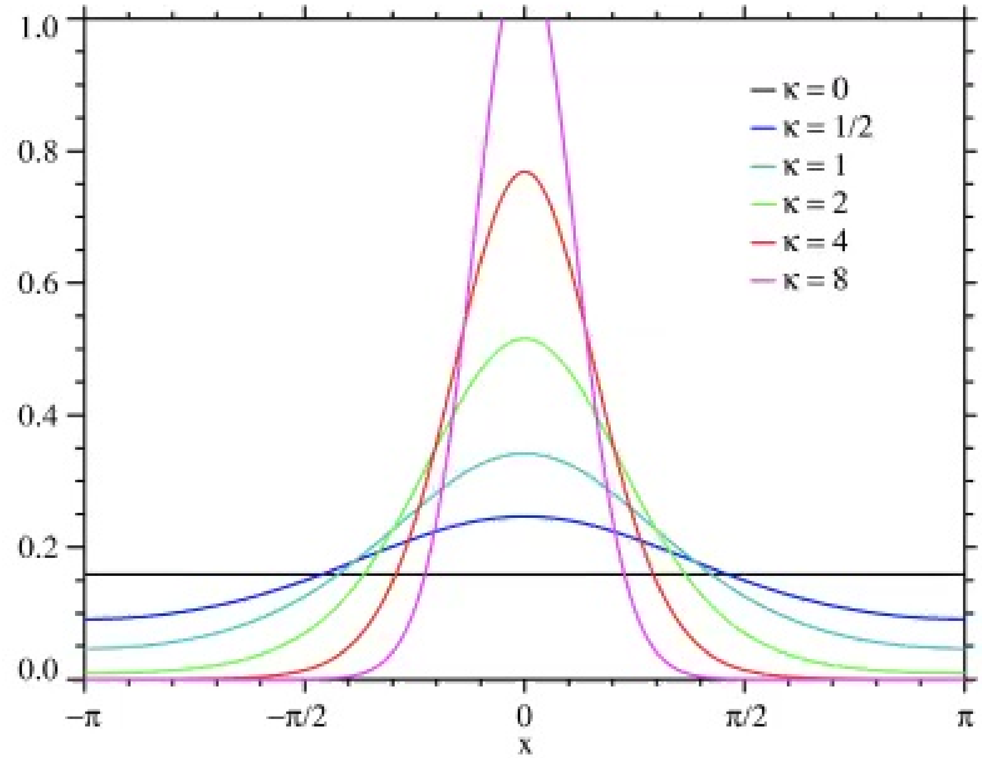
- Model ϕ_1, ϕ_{12} as being drawn from independent von Mises distributions parameterized by mean μ and width $\sigma \equiv 1/\sqrt{\kappa}$
- Approximately a Gaussian with periodic boundary conditions at $\pm\pi$



41

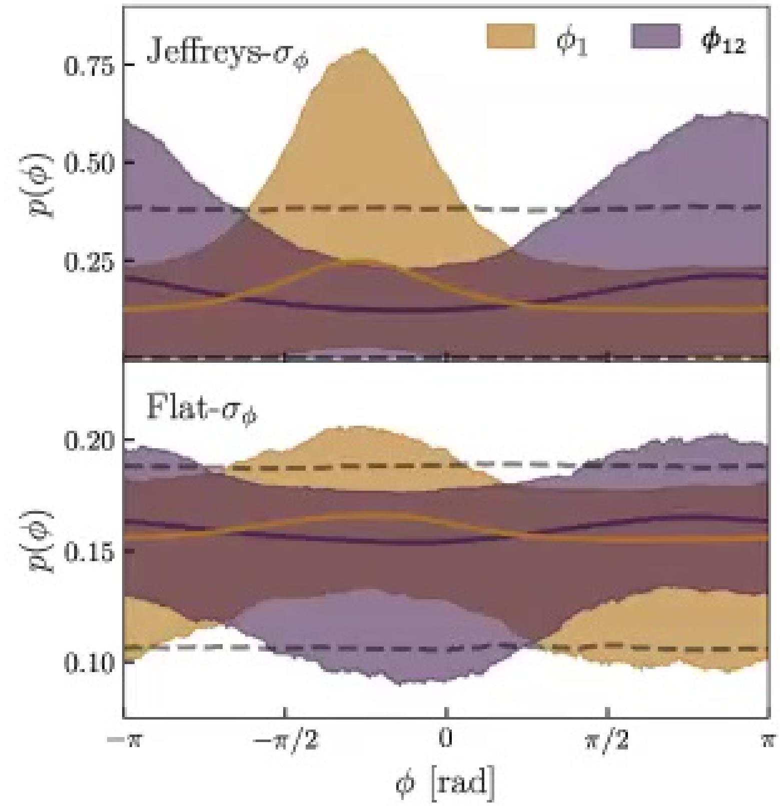
Azimuthal spin angles

- Model ϕ_1, ϕ_{12} as being drawn from independent von Mises distributions parameterized by mean μ and width $\sigma \equiv 1/\sqrt{\kappa}$
- Approximately a Gaussian with periodic boundary conditions at $\pm\pi$



Azimuthal spin angles

- Analyze 31 BBH events from GWTC-2 with total mass > 60 $M_\odot$ using NRSur7dq4 with spins specified at $t_{\rm ref}/M = -100$
- Apply two different priors on the width, uninformative measurement in both cases
- Mild preference for ϕ_1 to peak at $-\pi/4$ and ϕ_{12} to peak at $\pm\pi$

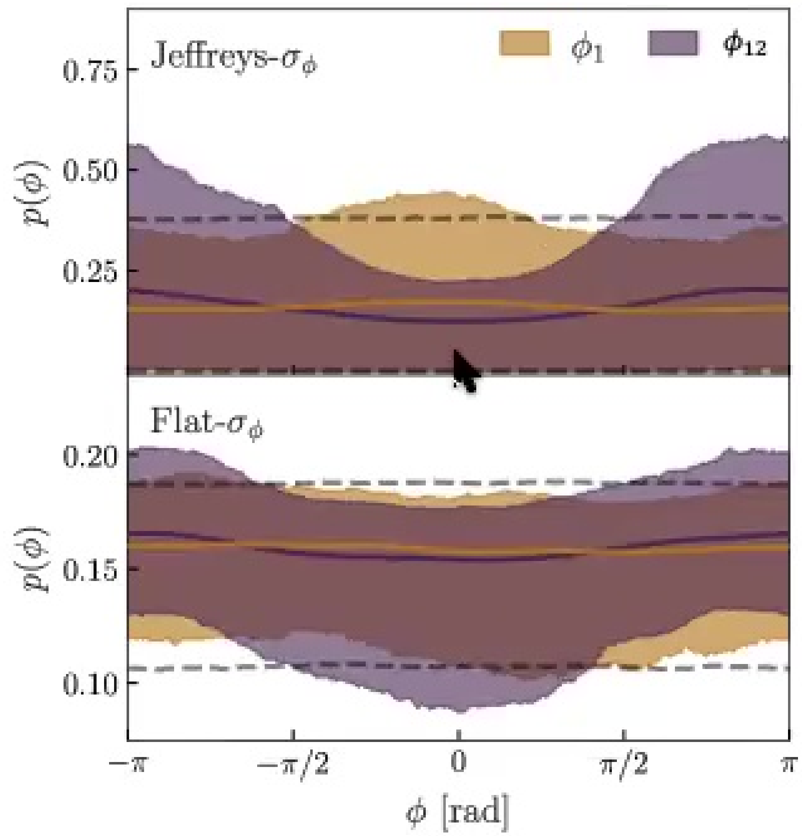


Varma, **S.B,** Isi, Farr, Vitale arxiv:2107.09693

42

Azimuthal spin angles

- Analyze 31 BBH events from GWTC-2 with total mass > 60 $M_{\odot}$ using NRSur7dq4 with spins specified at $f_{\rm ref} = 20$ Hz
- Apply two different priors on the width, uninformative measurement in both cases
- Mild preference for ϕ_1 to peak at 0 and ϕ_{12} to peak at $\pm\pi$



Varma, **S.B,** Isi, Farr, Vitale arxiv:2107.09693

Conclusions – Spin distributions

- Spin magnitude for highest-spinning black hole in the binary peaks at $\chi \approx 0.3$, lowest-spinning black hole spin peaks at $\chi = 0$
- Spin tilts are drawn from a nearly isotropic distribution – evidence for spin precession, extremely misaligned (negative) spins
- Tentative hint of spin-orbit resonances in the population, ϕ_1 at reference point near merger peaks at $-\pi/4$